One-handed Propulsion Control of Power-assisted Wheelchair with Advanced Turning Mode

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***Abstract*—The wheelchair is an important device that offers a method of transport to mobility-impaired people. For people also with hemiplegia or a hand/arm injury, a wheelchair operable with one hand is necessary. However, it is impossible to control a standard manual wheelchair or power-assist wheelchair with only one hand. An one-handed propulsion control system for a power-assisted wheelchair was proposed previously. This system allows the user to go straight and do pure rotations, but does not allow to turn the wheelchair while moving. In this paper, an improved one-handed propulsion system that realizes turning motion is proposed. The proposed method is verified experimentally to assess the ability to turn while on the move.**

***Keywords*—power-assisted wheelchair; one-handed propulsion; human-friendly motion control; hemiplegia**

I. Introduction

Mobility-impaired people need assistive devices for movement. There are many welfare devices which offer mobility-impaired people method of transport. Recently, exoskeletons have been developed as one such device, and there are many researches that focus on development and improvement of exoskeletons [1]-[2]. However, wheelchairs are still one of the most commonly used welfare device world-wide. As many different types of wheelchairs have been developed, wheelchair users are able to select a suitable wheelchair for their needs.

The main purposes of wheelchair research are to make wheelchairs safer [3]-[9], and to improve or develop handling methods [10]-[13]. Some researches are focused on realization of novel movement that was impossible in existing wheelchairs, such as step climbing [14]-[17]. There are research examples such as wheelchair dynamics or influence of front wheel [18]-[19]. Furthermore, there are researches about transfer motion or user-wheelchair interaction including injuries caused by using wheelchair [20]-[24].

There are many types of wheelchairs. A standard manual wheelchair is operated and gains propulsion by the user pushing its handrims with both hands. However, it is impossible for users with hemiplegia or a hand/arm injury to operate such a wheelchair. Furthermore, even if the wheelchair user is able to use both hands, there are many situations where the user may need to do something else with their hand while moving, such as opening doors or holding objects while moving.

In order to realize a wheelchair which can be operated by one hand, various one hand drive wheelchairs have been developed. The most popular way to operate a wheelchair with one hand is with a joystick. A joystick can be used even with a small movement of the hand, therefore, putting less burden on the user than a manual wheelchair would. However, even though using a joystick does not need much strength, there are users who have difficulty using a joystick [25]. Therefore, new interfaces and control systems are being developed, such as the neuronal joystick [26]. However, one major drawback of joystick use is, as the range of hand movement is small, muscle weakening will result in the absence of rehabilitation.

There is research focused on mechanical developments for realization of one-handed wheelchairs. One form of mechanical development is examples of wheelchairs with multiple handrims. These types of wheelchairs have handrims typically for going straight and turning, and the user pushes the appropriate hand rim to move in the desired manner. Recently, there are multi-rim wheelchairs that provide power assistance to reduce the burden on the user [27],[28]. However, having multiple handrims makes the wheelchair wider, and therefore unable to move around in confined spaces.

TrackChair, a wheel assembly kit for manual wheelchairs, is another example of mechanical development [29]. There are two handrims on each wheel — one drives the adjacent wheel while the other drive the opposite wheel. The user can either push one handrim of each side simultaneously or push both handrims of one side simultaneously to go straight. The main advantage of TrackChair is the ability to operate with both hands or with either hand. However, a large grip force is required to grab both handrims on a single side simultaneously.

Profhand is a pedaled wheelchair developed by TESS [30]. Unlike previous manual wheelchairs, Profhand is driven by pedaling like a bicycle, and direction is controlled by hand. It can keep the user active and free up one hand. However, it cannot be operated by users who cannot use both legs. Furthermore, the turning radii for left and right turns are different and are non-zero, which can make it difficult to navigate confined spaces.

The purpose of this research is to realize one-handed propulsion for a power-assisted wheelchair. It is impossible to control a standard manual wheelchair or power-assist wheelchair with only one hand. A one-handed propulsion control system for a power-assisted wheelchair that allows the user to go straight and do pure rotations was proposed previously, but this system didn't allow the user to turn the wheelchair while moving. In this paper, an improved one-handed propulsion system that realizes turning motion is proposed. In section II, the power-assisted wheelchair is introduced. In section III, previous works on an one-handed propulsion control system for the power-assisted wheelchair are introduced. The proposed one-handed propulsion system is introduced in section IV. Experimental results that verify the effectiveness of the proposed system, are shown in section V, and this paper is concluded in section VI.

II. POWER-ASSISTED WHEELCHAIR

Figure 1 shows the power-assisted wheelchair JW-II (Yamaha), which is used in the experiments of this paper. The power-assisted wheelchair is an electric wheelchair that has a motor in each of the two main wheels and a torque sensor in each handrim. The power-assisted wheelchair has been developed and researched [31]-[33].

When the user pushes a handrim, the user's pushing force is measured by torsion sensor in that handrim. The motors will output assist torque, that which is calculated in the assistive control system. The power-assisted wheelchair lightens the physical burden on the user by providing assistance, while encourages maintenance of arm function as well as improvement of health and fitness through handrim use. Also, by controlling both motors appropriately, wheelchair functionality as well as performance factors such as safety, comfort, handling and mobility can be enhanced. This research is aimed at proposing a practical one-handed propulsion system that takes advantage of the benefits of the power-assisted wheelchair.

The power-assisted wheelchair has the advantages below,

- it reduces burden on the user compared with the manual wheelchair,
- it still requires the user to push the handrims, which becomes exercise,
- it is easy to apply control systems,
- not too wide like multi-rim wheelchair,
- lightweight compared to most fully-electric wheelchairs.

Fig. 1. Power-assisted wheelchair *(Yamaha JW-II)*

III. CONVENTIONAL ONE-HANDED PROPULSION CONTROL SYSTEM

One-handed propulsion control for the power-assisted wheelchair was previously proposed [34]. Figure 2 shows part of the conventional one-handed control system block diagram, where disturbance observer is omitted in this figure. In [34], only straight motion and turning motion was realized. Mode coefficient K is decided by both the value and derivative of human torque, that is T_H and $\dot{T}_H$. Fuzzy division is implemented and sigmoid function is used to prevent rapid change. K is defined as follows:

$$K(T_H, \dot{T}_H) = sgn(T_H)\frac{1}{1+e^{-\beta(\dot{T}_H - \dot{T}_0)}} \qquad (1)$$

where $\dot{T}_0$ is a torque derivative threshold.

From Eq. (1), K can take values between 0 and 1. When K takes the value 1, the torque delivered to both wheels are equal, which makes the wheelchair go straight. After K becomes 1, straight mode (i.e. the state where $K = 1$) is kept until the wheelchair speed ω and human torque T_H become 0. When K is 0, the wheel opposite to the one being hand-driven has zero torque, which makes the wheelchair turn. Although straight motion and turning motion were realized, pure rotation was not possible with this control system.

To improve the capability and performance of one-handed propulsion, another control system was proposed [35]. In [35], a control system that realizes straight motion, turning motion and pure rotation motion was proposed. K was defined as follow,

$$K(T_H, \dot{T}_H) = \begin{cases} -1 & (T_H\dot{T}_H \leq 0) \\ \bar{K} & (T_H\dot{T}_H > 0) \end{cases} \qquad (2)$$

$$\bar{K} = \begin{cases} -1 & (|\dot{T}_H| < \dot{T}^r_{thr}) \\ 2\dfrac{|\dot{T}_H| - \dot{T}^r_{thr}}{\dot{T}^s_{thr} - \dot{T}^r_{thr}} - 1 & (\dot{T}^r_{thr} < |\dot{T}_H| < \dot{T}^s_{thr}) \\ 1 & (|\dot{T}_H| > \dot{T}^s_{thr}) \end{cases} \qquad (3)$$

where $\dot{T}^r_{thr}$ and $\dot{T}^s_{thr}$ are torque derivative thresholds for pure rotation and straight motion respectively.

The state flow chart for the conventional system [35] is shown in Fig.3. When K reaches 1, the wheelchair goes straight. Straight mode is kept for at least the duration t_{min}. While the wheelchair longitudinal speed exceeds ω^s_{off}, straight mode is maintained. When the speed drops below ω^s_{off}, straight mode ceases and the system enters stationary mode.

While K is -1, the torque delivered to the wheels are equal in magnitude but in opposition, which makes the wheelchair do pure rotations. This pure rotation was not possible with [34]. Furthermore, a "pure rotation mode" which allows for

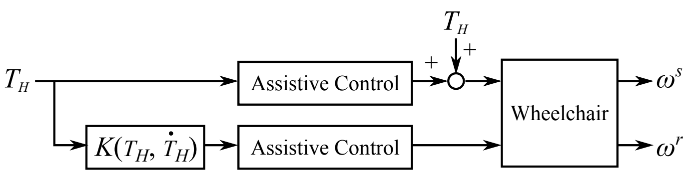

Fig. 2. Part of conventional one-handed control system block diagram

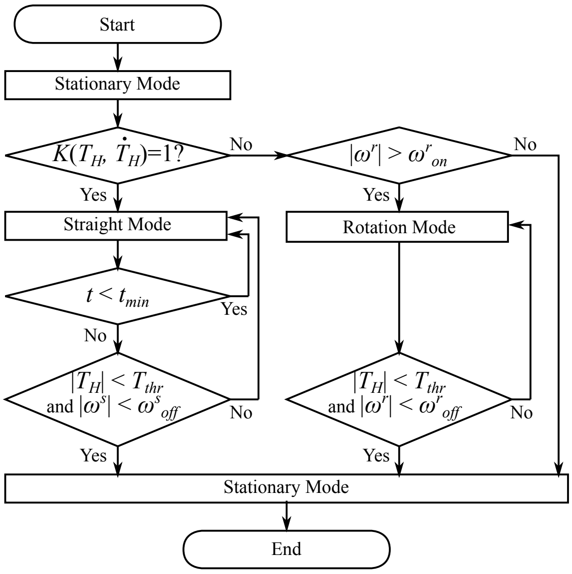

Fig. 3. State flow chart of conventional operation mode: No turning mode

rapid rotation was introduced in [35]. When the yaw rate ω^r exceeds the threshold ω^r_{on}, pure rotation mode is held. When the yaw rate drops below ω^r_{off}, pure rotation is no longer held and the system enters stationary mode.

IV. PROPOSED ONE-HANDED PROPULSION CONTROL SYSTEM

As mentioned in section III, conventional system [35] made improvements on [34] by making possible pure rotation by allowing K to take -1, and rapid rotation by introducing a pure rotation mode. However, the ability for the user to turn while moving straight was not implemented. To extend the capabilities of [35], an improved one-handed propulsion control system is proposed in this section.

Figure 4 shows a block diagram of the proposed one-handed propulsion control system. It is assumed that the user will push only one of the handrims. T_H denotes the left (or right) human torque. The operation mode block decides K based on the human torque signal along with its derivative and the wheel velocities. The assistive control block calculates the assist torque to be generated by the motors. Torque inputs to the assistive control block are T_H for the same side as the user's operating hand, and KT_H for the other side. The assistive control system contains two variable-bandwidth low-pass filters, one to amplify straight torque and the other to amplify rotational torque, to provide assistance for straight motion and

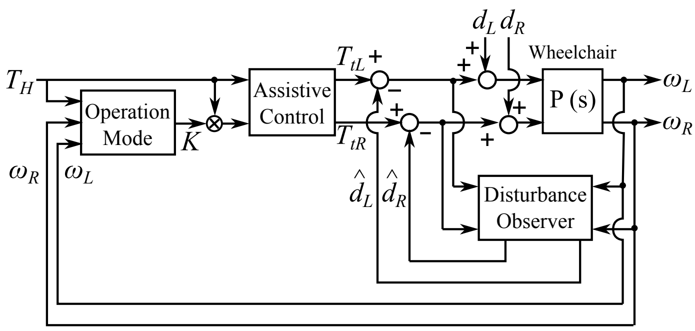

Fig. 4. Block diagram of proposed one-handed control system

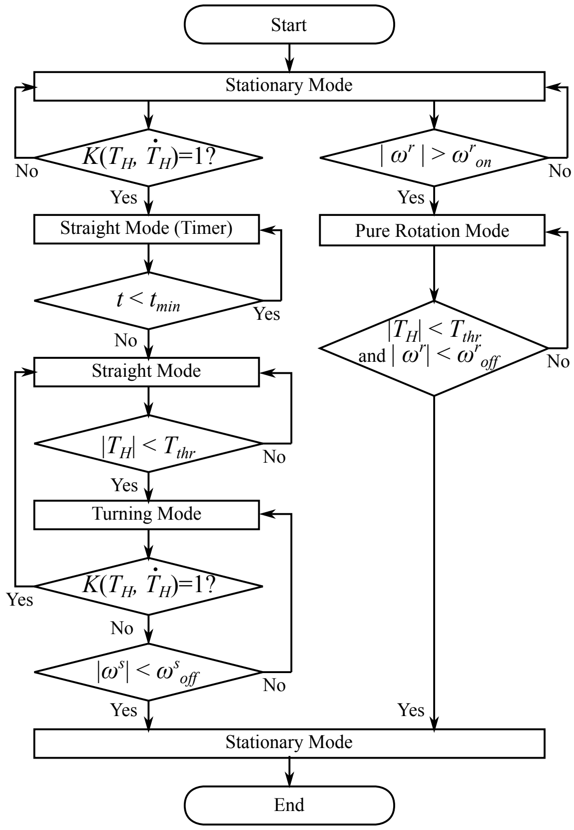

Fig. 5. State flow chart of operation mode: turning mode included

rotational motion independently [36]. The disturbance observer estimates external torques, and these estimates are fed back negatively to compensate for environmental disturbances and modeling errors.

A. Operation mode

1) Definition of K: Human torque T_H and its derivative $\dot{T}_H$ are used to decide operation mode. K is defined by Eq. (2) and Eq. (3). When $T_H\dot{T}_H > 0$ and $|\dot{T}_H| > \dot{T}^s_{thr}$, K will take the value 1, where pushing the handrim will make the wheelchair go straight. On the other hand, K will be -1 when $T_H\dot{T}_H < 0$ or $|\dot{T}_H| < \dot{T}^r_{thr}$, where pushing the handrim will make the wheelchair rotate. When $T_H\dot{T}_H > 0$ and $\dot{T}^r_{thr} < |\dot{T}_H| < \dot{T}^s_{thr}$, K will be between -1 and 1.

2) Straight mode: Figure 5 shows the state flow chart of the operation mode block. If K becomes 1 while in stationary mode or turning mode, the mode will change to "straight mode". There is a minimum straight mode hold time of t_{min}. This minimum hold time facilitates fine control of straight movement while straight mode is held, which is achieved by the user initially pushing the handrim a moderate but high-derivative torque (such that K becomes 1). After entering straight mode, when $|T_H| < T_{thr}$, $K < 1$ and $|\omega^s| < \omega^s_{off}$, i.e. when the user doesn't touch the handrim and the wheelchair slows down, the mode will change to stationary mode.

3) Pure rotation mode: If $K < 1$ and $|\omega^r| > \omega^r_{on}$, i.e. when the human torque isn't sudden and the yaw rate exceeds the threshold $R\omega^r_{on}$, the system will enter "pure rotation mode". While in pure rotation mode, K is held at -1, and therefore the use can make the wheelchair rotate rapidly by applying far greater torque. When $|T_H| < T_{thr}$ and $|\omega^r| < \omega^r_{off}$, the system will return to stationary mode.

4) Turning mode: Changing direction while the wheelchair is moving straight is made possible by the "turning mode". This is biggest difference between the previous one-handed propulsion control system and the one proposed in this paper. After entering straight mode, when the handrim is not being operated and time t_{min} has passed, the system enters turning mode. In this mode, the user is able to turn the wheelchair by pushing the handrim with torque such that $K < 1$. The user can also continue to propel the wheelchair straight by pushing the handrim with torque such that $K = 1$, i.e. with sufficient torque derivative. By using this algorithm, turning without stopping the wheelchair is made possible.

B. Assistive control system

Figure 6 shows assistive control system [36]. It is two-dimensional assistive control that provides power assistance for straight and rotational motion independently. T_{hL} and T_{hR} are user's propulsion torque of left and right side. The left and right motor assist torques are defined in Eq. (4) and Eq. (5) as follows:

$$T_{aL} = T_a^s - T_a^r = \frac{\alpha_s}{\tau_a^s s + 1} T_H^s - \frac{\alpha_r}{\tau_a^r s + 1} T_H^r \quad (4)$$

$$T_{aR} = T_a^s + T_a^r = \frac{\alpha_s}{\tau_a^s s + 1} T_H^s + \frac{\alpha_r}{\tau_a^r s + 1} T_H^r \quad (5)$$

where α^s and α^r are the assist gains for the straight and rotational components respectively. Time constants τ_a^s and τ_a^r for the straight and rotational components respectively are defined as follows:

$$\tau_a^s = \begin{cases} \tau^s_{fast} & \left(\dfrac{dT_H^s}{dt} \geq 0\right) \\ \tau^s_{slow} & \left(\dfrac{dT_H^s}{dt} < 0\right) \end{cases} \quad (6)$$

$$\tau_a^r = \begin{cases} \tau^r_{fast} & \left(\dfrac{dT_H^r}{dt} \geq 0\right) \\ \tau^r_{slow} & \left(\dfrac{dT_H^r}{dt} < 0\right) \end{cases} \quad (7)$$

where $\tau^s_{fast} < \tau^s_{slow}$, $\tau^r_{fast} < \tau^r_{slow}$ and $\tau^s_{slow} > \tau^r_{slow}$.

The fast time constants τ^s_{fast} and τ^r_{fast} are chosen to be small (0.08 seconds) so that assistance torque rises rapidly when the user handrim force increases. The slow time constants τ^s_{fast} and τ^r_{fast} are chosen to be large (1.0–1.5 seconds) so that assistance is provided even after the user finishes pushing the handrim. The slow time constants τ^s_{slow} and τ^r_{slow} can be chosen independently, and for improving handling for straight and rotational operation it is effective to do so [36]. Time constants τ_a^s and τ_a^r were designed in experiments to obtain good handling.

C. Disturbance observer

Block diagram of disturbance observer is shown in Fig. 7.

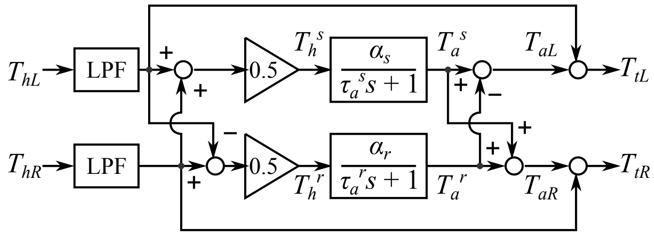

Fig. 6. Block diagram of assistive control system

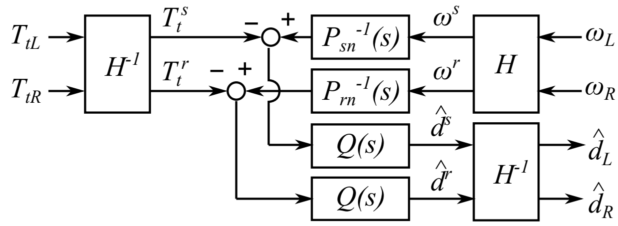

Fig. 7. Block diagram of disturbance observer

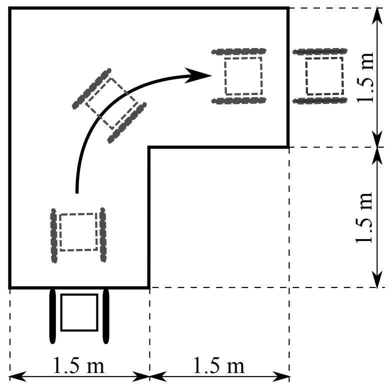

Fig. 8. Experiment: Right turn *(Top view)*

H is a transformation matrix, defined in (8), that turns wheel velocities expressed as left-right components, ω_L and ω_R, into straight-rotational components, ω^s and ω^r.

$$H = \begin{bmatrix} 1/2 & 1/2 \\ -1 & 1 \end{bmatrix}, H^{-1} = \begin{bmatrix} 1 & -1/2 \\ 1 & 1/2 \end{bmatrix} \quad (8)$$

T_{tL} and T_{tR} are the total torques of the left and right side respectively, which are the addition of human torque and assist torque. T_t^s and T_t^r the total torques expressed as straight and rotational components. ω_L and ω_R are the left and right wheel velocities. d_L and d_R are the disturbance torques on the wheels, and $\hat{d}_L$ and $\hat{d}_R$ are their estimates. Disturbance estimation is done in terms of straight and rotational components, and the converted into left and right components. $P_{sn}(s)$ and $P_{rn}(s)$ are nominal models of the straight and rotational dynamics of the wheelchair, and $P_{sn}^{-1}(s)$ and $P_{rn}^{-1}(s)$ are their inverses. $Q(s)$ represents a filter that is required to realize the inverse models.

V. Verification of Turning Operation with the Proposed System

A. Experimental environment

The purpose of the experiment in this section is to verify turning operation with the proposed control system. Figure 8 shows the experimental environment. Turning operation was verified with a single right-hand turn while moving forward. Parameters used in experiments are shown in Table I.

TABLE I. PARAMETERS USED IN EXPERIMENTS

assist rate (straight)	α_s		2.0
time constant (straight)	τ_a^s	τ_{fast}^s	0.08 s
		τ_{slow}^s	1.5 s
assist rate (rotation)	α_r		2.5
time constant (rotation)	τ_a^r	τ_{fast}^r	0.08 s
		τ_{slow}^r	1.0 s
Forward high threshold	$\dot{T}_{thr}^s$		70.5 Nm/s
Differential torque low threshold	$\dot{T}_{thr}^r$		69.5 Nm/s

B. Conventional one-handed propulsion control system

The experimental result for the conventional control system is shown in Fig. 9. The first graph shows the left and right wheel velocities as a red solid line and a blue dashed line respectively, and the difference between the two is shown as a green dash-dot line. The second graph shows human propulsion torque T_H and torque of the opposite side KT_H as a red solid line and a blue dashed line respectively, and the difference between the two is shown as a green dash-dot line. The third graph shows K and the system's mode of operation. Stationary mode is 1, straight mode is 2, and pure rotation mode is 3. The last graph shows yaw rate γ of the wheelchair, as measured by the on-board gyroscope.

Between 9 and 16 seconds and between 21 and 30 seconds, the angular velocity of the two wheels are almost the same and the yaw rate is small. Between 16 and 21 seconds, the angular velocity the two wheels are roughly equal and opposite, and the yaw rate is large. The results indicate that the wheelchair moves forward from a stationary state, stops, does a pure clockwise rotation, stops, moves forward again, and finally stops.

The conventional system does not allow the user to make the wheelchair turn while it is moving longitudinally. Therefore, in order to turn a corner or even adjust heading, the user must stop the wheelchair to change modes. This is shown in the results, between 15 and 16.5 seconds and between 18 to 20.5 seconds, where user stops the wheelchair to change mode.

C. Proposed one-handed propulsion control system

The experimental result for the proposed control system is shown in Fig. 10. Graph information is the same as in Fig.9 except for the mode numbers in the third graph. There are 5 modes in the proposed control system: stationary mode is 0, straight mode (timer) is 1, pure rotation mode is 2, turning mode is 4, and straight mode is 5.

Between 9 and 10.5 seconds, the angular velocities of the two wheels are roughly the same, and the wheelchair is moving forward. Between 10.5 and 23 seconds, the angular velocity of the left wheel is more positive than that of the right wheel, which indicates the wheelchair is turning right while moving forward.

Between 9 and 21 seconds, the wheel is continually in motion and does not stop. The user continually pushes the handrim to make the wheelchair go straight or turn right, and does not make the wheelchair stop.

The system's mode of operation is shown in the third graph. Between 9 and 10 seconds, the system is in straight mode (timer). Afterwards, between 10 and 14 seconds, the system switches between straight mode and turning mode depending on whether the user pushes the handrim to go straight or to turn. Between 14 and 15 seconds, the system stays in turning mode, and the yaw rate is shown to get large. This process is repeated between 15 and 18 seconds and between 18 and 23 seconds.

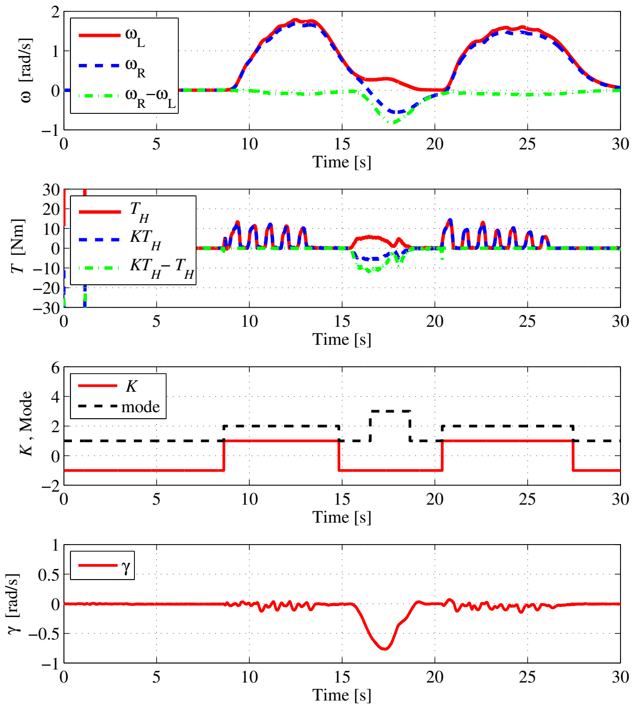

Fig. 9. Experimental result of conventional control system

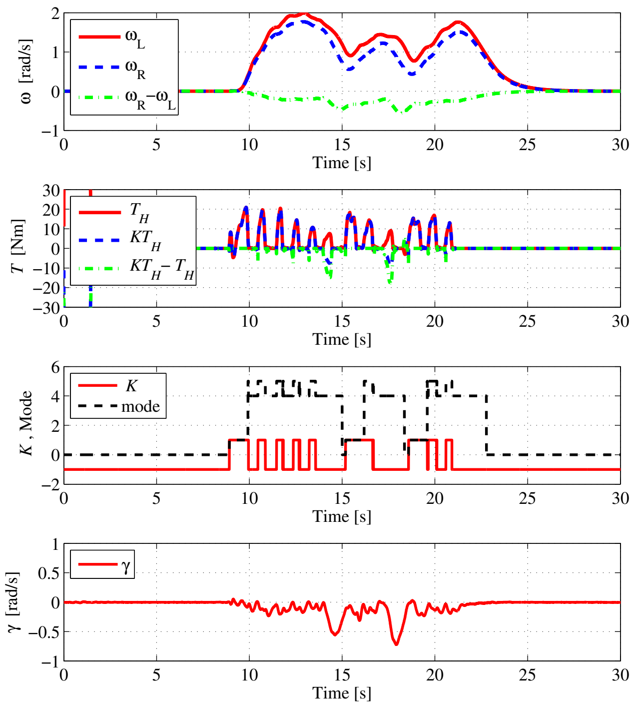

Fig. 10. Experimental result of proposed control system

VI. Conclusion

This paper proposes an improved one-handed propulsion control system for the power-assisted wheelchair, which adds the ability to turn while the wheelchair is moving longitudinally. The system's mode of operation is controlled by state flow logic, and is primarily decided by the derivative of the user's handrim torque signal.

With the proposed system, it is also possible to make the wheelchair go straight, do pure-rotation and turn on the move, all by operating the wheelchair with one hand. It is verified experimentally that the proposed control system realizes turning on the move, which was impossible with the previous control system. With the previous system, the user has to stop the wheelchair to change the system's mode of operation. The experiment shows that with the proposed system, the user is able to change between straight mode and turning mode while the wheelchair is in motion.

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